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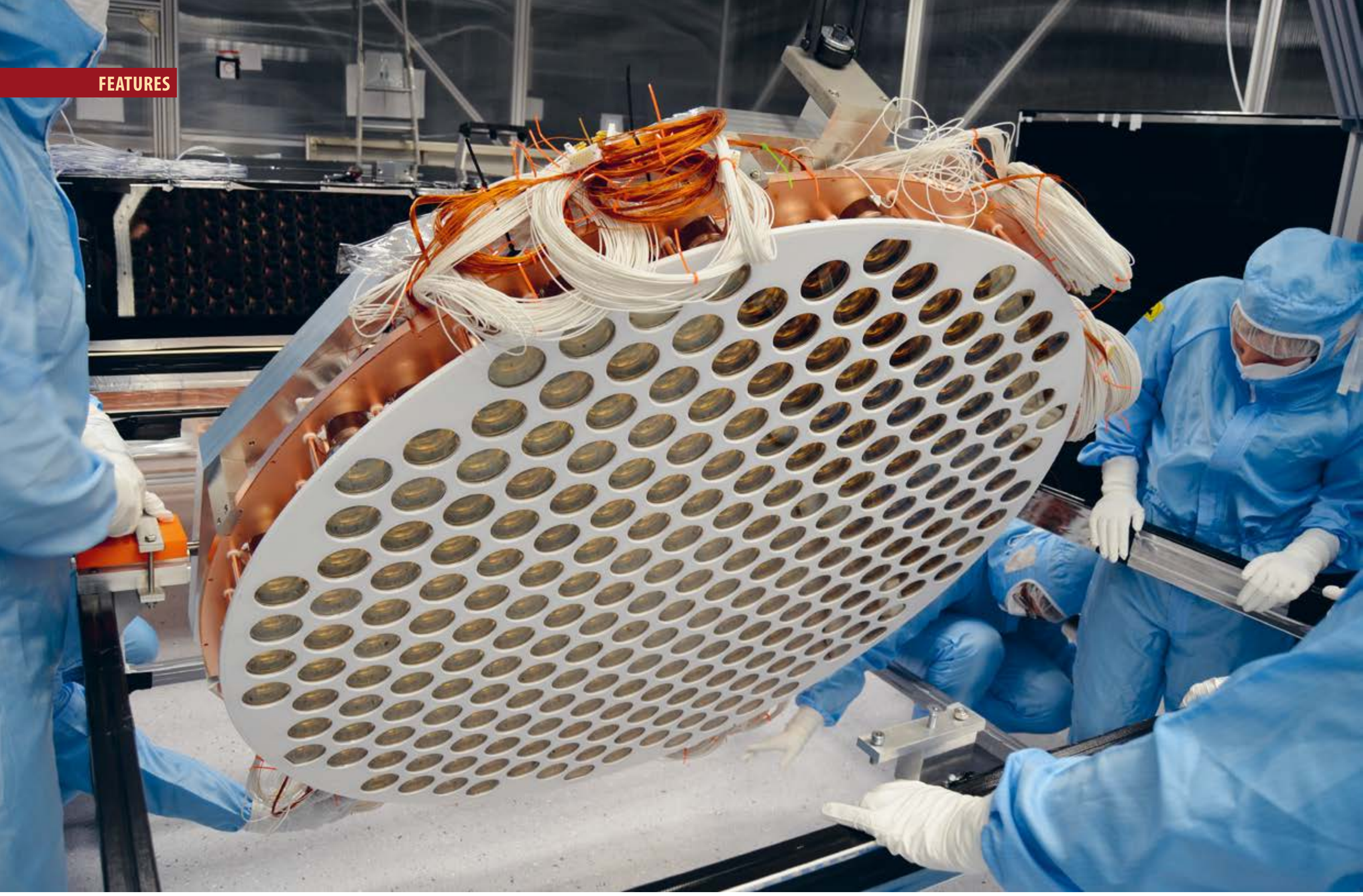

CRYOGENIC DARK MATTER SEARCHES

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In the decades-old quest to uncover the nature of the enigmatic dark matter, cryogenic detectors have reached unprecedented sensitivities. Searching for tiny signals from dark matter particles scattering in materials cooled down to low temperatures, these experiments look out into space from deep underground. Their ambitious goal is to discover non-gravitational interactions of dark matter and to scan the allowed parameter space until interactions from solar and cosmic neutrinos are poised to take over.

▲ Installation of the top photosensor array of the XENONnT experiment in a cleanroom at the Gran Sasso Underground Laboratory. Photo credit: the XENON collaboration)

The matter density in the Universe has been on the minds of cosmologists for over a hundred years, for it determines its geometry and expansion rate. Another intriguing question is its composition: only 15% is made of baryons, the matter of stars and stellar remnants, of interstellar and intergalactic gas. This component can emit or absorb radiation from the radio, infrared, visible, ultraviolet to the X-ray and gamma range of the electromagnetic spectrum, and thus be observed with ground- or space-based telescopes. For almost a century we know however that the majority of matter is non-baryonic: it does not emit, absorb or scatter light, and so far has only been observed through its gravitational influence on luminous matter [1]. One of the major open questions is this: What is the composition of dark matter? Is it made of new elementary particles or primordial black holes, or perhaps both, is it one species of particles or many? While we can chart the distribution of dark matter from galaxies to the largest observed structures and measure its density in the early Universe and today, we are in complete darkness when it comes to the essential question: What is it and how does it interact with visible matter?

Dark Matter and its Distribution in the Milky Way

Conjectures about the nature of dark matter span more than eighty orders of magnitude in mass — from ultra-light, or wave-like dark matter with a mass of 10^{-22} eV/c^2 to primordial black holes with up to tens of solar masses — and many orders of magnitude in interaction strengths with baryonic matter. While no particle of the Standard Model is a good candidate, any contender must be consistent with a vast range of astrophysical and cosmological observations, while also satisfying constraints from laboratory searches [2]. The question on the nature of dark matter is intrinsically connected to the physics of the energetic, early Universe, when a dark species could have been produced together with neutrinos, electrons, quarks, photons and other known particles[1]. This dark species provided the extra gravitational force, allowing structures to form from initial, small irregularities due to quantum fluctuations, and in particular lead to the formation of spiral galaxies like our own. Some of the most appealing candidates are axions, with masses at the μeV/c^2 scale, and weakly interacting massive particles (WIMPs), with masses from a few GeV/c^2 (where the mass of the proton is about 1 GeV/c^2) to ~ 100 TeV/c^2.

The luminous structure of the Milky Way thus resides in an extended, roughly spherical dark matter halo with radius of ~100 kpc (an order of magnitude beyond the baryonic disk), implying a total mass of ~10^{12} solar masses. From the measured galactic rotation curve and the kinematics of stars as tracers for the dark matter and hence the underlying gravitational potential, one can derive the density and velocity of dark matter. At the solar system's location, 8 kpc away from the Galactic Centre, the dark matter density is around 0.3 GeV/cm^3 (or equivalently, 0.008 solar masses/pc^3), while the average speed is ~200 km/s [3].

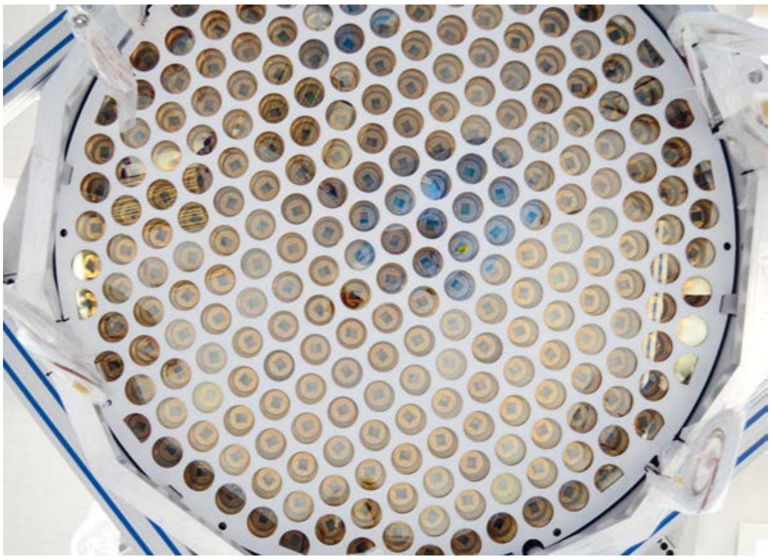
Direct detection experiments in silent locations

One of the main laboratory probes of dark matter in the Milky Way is called direct detection. Experimentalists aim to record those ultra-rare occasions when an invisible particle scatters in a target material. As we move, together with the Sun, around the Galactic Centre and through the dark halo, we encounter a wind of dark matter particles. Their density and velocity distribution, together with their mass and interaction strengths, determine the expected scattering rates in a detector, as well as the deposited energies. The latter are tiny, at the keV-scale and below, while from the fact that we haven't seen any convincing signal in a direct detection experiment so far, the rates are smaller than one per kilogram or tonne of target material and year for masses below and above a few GeV/c^2, respectively. These are almost unthinkable low rates, millions of times below those expected from cosmic ray interactions at the Earth's surface, requiring that detectors are operated in deep underground laboratories. An underground location is far from sufficient. The experiments must also be placed in extremely quiet environments: shielded from the natural radioactivity of their immediate surroundings, and purified from potential nuclides which can emit alpha, beta and gamma radiation when they decay inside the target material and possibly mimic the expected signal. After about three decades of development, two technologies are reaching unprecedented sensitivities in the search for dark matter interactions: ultra-pure, liquified noble gas detectors using liquid argon and xenon, and crystals operated only a few tens of degrees above the absolute zero [4].

Liquified noble gas detectors

From all noble elements, only argon and xenon are currently employed as targets for dark matter detection, while R&D on helium is ongoing. In their liquid phase, argon (at T~87 K) and xenon (at T~165 K) are outstanding media for building large, homogeneous, compact and self-shielding detectors which can reach ultra-low backgrounds at their cores. Both liquid argon and xenon are excellent scintillators and good ionisers in response to the passage of radiation. The simultaneous detection of light (in the VUV-region at 128 nm and 175 nm respectively) and charge leads to a good energy resolution and the identification of the primary particle interacting in the liquid, an essential feature for picking out a signal-like interaction from background. In addition, the three-dimensional mapping of the spatial position of scatters in time projection chambers (TPCs) allows to select single-events— as expected from dark matter particles — from multiple interactions in the detector. One of the challenges in noble liquids is their purification from radioactive isotopes which are either present in the atmosphere (^{39}Ar, ^{85}Kr) or emanated by detector materials (^{222}Rn) and, mixed with the liquid, lead to backgrounds due to beta- and alpha-radiation. Depletion by isotopic separation in large-scale cryogenic distillation columns, and by extraction from underground wells, in case of argon, have lead to concentrations within about a factor of ten from those needed to reduce these contributions below those from elastic scatters of solar • • •

[1] Primordial black holes are thought to originate from gravitational collapse of large density fluctuations in the early Universe



▲FIG. 1: The top photosensor array of the XENONnT dark matter detector. With 8.6 tons of liquid xenon in total, the experiment will start a first science run at the Gran Sasso Underground Laboratory in Italy in spring 2021 (Photo credit: the XENON collaboration).

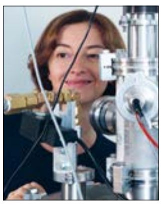
• • • pp-neutrinos with electrons. A previous generation of argon and xenon TPCs (DarkSide-50, LUX, PandaX-II, XENON1T) has probed a large part of the theoretical parameter space for particles with masses above a few GeV/c^2, reaching interaction cross sections on nucleons as low as 10^{-47} cm^2 at 30 GeV/c^2. To set this into perspective, the cross section of neutrinos generated in beta-decays, thus with energies around 1 MeV, is ~ 10^{-44} cm^2. Experiments to acquire data in the next few years or currently in construction, with multi-tons of noble liquids as dark matter target (LUX-ZEPLIN, XENONnT, PandaX-4T, DarkSide-20k) and in planning (DARWIN, ARGO) will have a fair chance to unveil first, feeble signs of dark matter interactions [5]. Once such a direct evidence for a signal has been established, the focus will shift towards measuring the properties of the dark species, such as their mass, interaction cross section and possibly spin.

Crystals at mK temperatures

The development of cryogenic experiments operated at sub-Kelvin temperatures has been driven by the exciting possibility to perform a calorimetric measurement down to very low energies, with unsurpassed energy resolution. Because of the T^3-dependance of the heat capacity of a dielectric crystal, at low temperatures a small energy deposition can significantly change the temperature of the absorber. As an example, at a temperature of 10 mK, a 1 keV energy deposition in a 100 g detector increases its temperature by about 1 μK. This change in temperature is measured either after the phonons reach equilibrium, or thermalise (*e.g.*, with neutron transmutation doped sensors), or when they are still out of equilibrium, or athermal (*e.g.*, with transition edge or kinetic inductance sensors), the latter also providing information about the location of an interaction in the crystal. Dark matter detectors based on the bolometric technique also read out ionisation in semiconductors (EDELWEISS, with Ge crystals, and SuperCDMS, with Ge and Si crystals) or the scintillation light in a transparent crystal (CRESST, with $CaWO_3$ crystals), since the ratio of the two signals allows to differentiate between different type of interactions. Recently, these experiments were optimised for light dark matter searches, with sub-GeV/c^2 masses. One avenue is to operate the detectors at higher bias voltages and to amplify the phonon signals produced by drifting charges, exploiting the Neganov-Trofimov-Luke effect. As an example, an energy threshold of 56 eV was reached by SuperCDMS for a bias voltage of 70 V across a 600 g Ge crystal. Another direction is to decrease the size of the crystals, as followed by CRESST, where energy thresholds around 100 eV were achieved with 24 g $CaWO_3$ crystals. Some of the challenges of future bolometric dark matter detectors are to increase the surface area coverage of phonon sensors, the fabrication of transition edge sensors with lower operational temperatures to further decrease the noise and thus energy thresholds, as well as background control. New purification and in-house crystal growth techniques are developed, and underground crystal growth and detector development to avoid activation by cosmic rays are considered [5].

Outlook

We live in a vast sea of dark matter, but its composition at the fundamental level remains an enigma. Cryogenic experiments based on liquefied noble gases and crystals operated at a few tens of degrees above the absolute zero have demonstrated the highest sensitivities to feeble and ultra-rare scatters for a wide range of dark matter particles. While the pragmatic goal is to probe the theoretically allowed parameter space until interactions from cosmic neutrinos will take over, these experiments might well herald one of the greatest discoveries in twenty-first century physics. ■



About the author

Laura Baudis is a professor in the Physics Department of the University of Zurich. She has a long interest in dark matter and neutrino physics and has worked with cryogenic detectors since her days as a PhD student in Heidelberg. She is one of the founders of the XENON programme and leads the DARWIN collaboration with the aim to build an observatory based on a 40 t liquid xenon time projection chamber.

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